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Hydrodynamic Cavitation

Hydrodynamic cavitation is a phenomenon of formation, growth and collapse of vapor filled cavities (micro bubbles) within a liquid due to variation of local pressure. The cavities are generated in a low pressure region. When these cavities travel to a region of higher pressure, they implode (collapse). The cavity collapse under certain conditions results in very high pressures and temperatures near the location of collapse [1–3]. These extreme temperatures (>2000 K) and pressures (>100 MPa) result in the generation of highly reactive radical species (from water and dissolved gases). In addition, the imploding cavities also result in high velocity jets and intense shear. These extreme physio-chemical effects produced by cavitation have been of interest to engineers and scientists for over a century, largely due to its potential to damage equipment. The mechanisms of cavitation damage have been and continue to be hotly debated, and to this day the causes and effects of cavitation still present fundamental scientific challenges to engineers; for example, continuing issues in the field of water turbines described by the “three gorges puzzle” [4].

The extreme conditions generated during cavitation can also be harnessed for realizing beneficial physico-chemical transformations. In the last couple of decades, the application of cavitation has been extensively explored for a variety of physical, chemical and biological processes. Cavitation offers a novel way of intensifying these processes in an energy efficient manner [5, 6]. The in situ generation of strong oxidants like OH· radicals, local hot spots and intense shear, has a potential to become a very promising technology platform for realizing various transformations (see Figure 1.1). It can be harnessed for waste water treatment [7–12]; microbial disinfection [13–17]; desulphurisation of fuels [18–20]; biomass pre-treatment [21–23]; biodiesel synthesis [24, 25]; and in food and beverage production [26, 27]; esterification reactions [28]; and many other process intensification applications [3, 5, 6, 29, 30].

The references cited here represent only a tiny fraction of illustrative examples from published laboratory studies on applications of hydrodynamic cavitation. There are also several patents and start-up/spin-out companies commercializing cavitation based technologies and applications. See for example, reviews by Carpenter et al. [5] and Holkar et al. [6]. Despite such a large number of publications

Hydrodynamic Cavitation: Devices, Design, and Applications, First Edition.
Vivek V. Ranade, Vinay M. Bhandari, Sanjay Nagarajan, Varaha P. Sarvothaman and Alister T. Simpson.

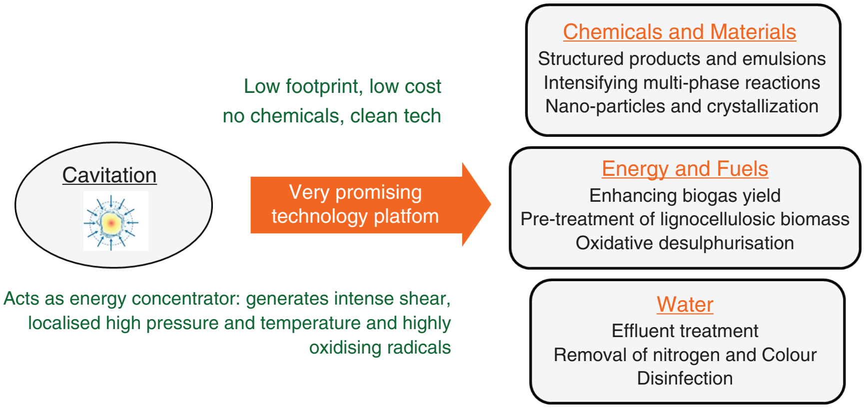

Figure 1.1 Cavitation for beneficial physico–chemical transformations.

on cavitation (thousands of research papers per year – Google Scholar), the promise of hydrodynamic cavitation as a technology platform is still largely unfulfilled. One of the key reasons of holding back the realization of this promise is inadequate understanding of inception as well as resulting physico-chemical effects of cavitation. Systematic methodology for designing hydrodynamic cavitation devices and generalized framework for development and optimisation of hydrodynamic cavitation processes is still not established and available.

Mathematical modeling of hydrodynamic cavitation and the related physico-chemical effects is rather complex even for the simplest devices and systems. Dynamics of a single cavity and subsequent collapse when exposed to adequately strong pressure fluctuations has been studied for long since Lord Rayleigh [31]. The book by Brennen [1] provides detailed models as well as results of cavity dynamics. The quest for developing better models for simulating cavity dynamics is still continuing (see for example, Pandit et al. [32] and references cited therein). Though such single cavity models are available, use of these models for simulating overall performance is still far from satisfactory. The book by Shah et al. [2] has attempted to present a methodology for systematic analysis of cavitation processes and discussed possible pathways for connecting single cavity dynamics to overall performance. Franc and Michel [33] published a book on fundamentals of cavitation. However, the focus was mainly on hydrodynamics and various applications were not discussed. About a decade ago, Ozonek [34] attempted to present a methodology for applying hydrodynamic cavitation primarily to water treatment applications. There are couple of reviews from the group of Professor Pandit [30, 35] with discussion on design aspects of orifice and venturi based hydrodynamic cavitation.

None of the available resources provide systematic basis for designing and evaluating different hydrodynamic cavitation devices or for simulating overall performance and scale-up of processes based on such devices. This book attempts to bridge this gap. This chapter provides a general introduction to hydrodynamic cavitation and devices to realize hydrodynamic cavitation. It also presents overall structure of the book to facilitate better usage of the presented contents.

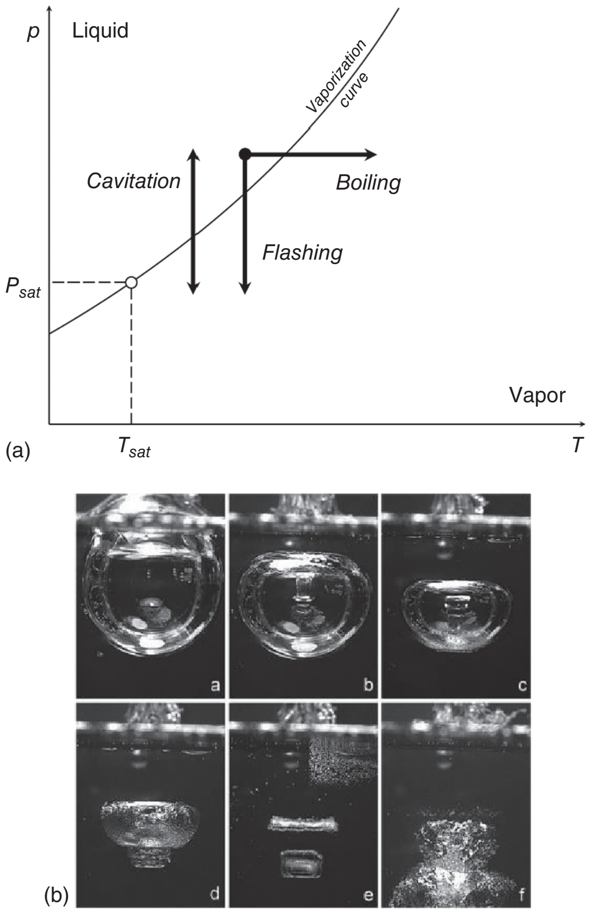

Figure 1.2 (a) Boiling and cavitation illustrated in thermodynamic diagram (Source: Reprinted from [36], with permission from Meijn/Delft University of Technology) and (b) Graphic illustration of growth, implosion and collapse of bubbles in the cavitation process (Source: Reprinted from [37], with permission from Elsevier).

1.1 Hydrodynamic Cavitation

Cavitation in a simple sense is the phenomenon of formation, growth and collapse of gaseous pockets in a liquid medium due to a dynamic pressure change in the bulk of the medium. When a liquid is subjected to a pressure below its vapor pressure, there is a possibility of generating a cavity or a gaseous bubble which is called as cavitation (see Figure 1.2a). In absence of any nuclei, liquid phase is able to withstand negative pressure (with respect to its vapor pressure) without rupturing or forming vapor cavities. In such cases, cavitation may occur via homogeneous nucleation (formation of small nuclei – transient gaps between molecules caused by random motions of the molecules). However, in most of the real life cases, liquid contains tiny suspended particles or some dissolved gases. These particles or desorption of dissolved gases provide nucleation sites for cavitation. In the presence of such heterogeneous nucleation, cavitation may be assumed to occur when local pressure falls below vapor pressure of liquid.

When a cavity generated in a manner described above is subjected to varying pressure field, complex process of expansion and contraction may occur eventually leading to the collapse of the cavity. Cavity dynamics is generally quite fast and has been extensively investigated. The experimentally visualized growth and collapse of a typical cavity is shown in Figure 1.2b. The collapse of cavities give rise to high velocity jets, very high localized pressure and temperature as well as results in the generation of hydroxyl radicals [3, 32]. The intense shear and hydroxyl radicals generated by collapsing cavities and resulting physico-chemical transformations have been of interest to scientists and engineers for over a century to either develop approaches for avoiding them or harnessing them for variety of desired applications [38].

The history of this phenomenon can be traced back to it being proposed as the possible reason for reduced efficiency of a warship – HMS *Darling* back in 1885. The phenomenon was thought to be responsible for the formation of gaseous pockets at very high speeds in naval structures and thereby reducing its efficiency. Barnaby [39, 40] wrote papers to describe the phenomenon of creation of voids and cavities, below a certain low pressure. Lord Rayleigh formalized these discussions and theoretically proposed mechanisms for the cavitation phenomenon in 1917, which has been improved until now to develop the current understanding on the mechanism of cavitation. There is evidence that the phenomenon was anticipated as early as 1704 by Newton and further in the works of Euler and Reynolds in the nineteenth century [41]. A detailed historical account of the origin prior to Lord Rayleigh's work is succinctly provided by Young. The historical aspects such as the coinage of the word and earlier theoretical descriptions of existence of such a phenomenon exist prior to Lord Rayleigh's work [33], but for all practical purposes, theoretical investigation and the foundation of the current understanding was from the early twentieth century.

Depending on the way of generation, four types of cavitation processes are known: optical, particle, acoustic and hydrodynamic cavitation. The cavitation phenomena realized by optic and particle methods are not widely investigated, as they are not suitable for effecting change in bulk solutions and have very limited applicability to chemical processing [42, 43]. Acoustic cavitation, as evident from its name, uses ultrasound for generating cavitation. When high frequency sound waves (20 kHz to 200 MHz) of adequate intensity are passed through a liquid, local pressure may dip below the vapor pressure and cavitation may occur. Ultrasonic cavitation was first used to accelerate chemical reactions in 1927 [44]. Since then, several papers have been published on a wide range of applications of ultrasonic cavitation. For example, chemical reactions [45, 46], homogenization [47, 48], cell disruption [49, 50], dentistry [51] among other niche applications such as imaging of foetus [52] and physiotherapy [53]. A recent book edited by Ashokkumar [54] provides an excellent compilation on ultrasonic cavitation and its applications. Despite several published studies on numerous applications, industrial applications of ultrasonic cavitation are rather limited barring a few exceptions. This may be because of inability to distribute cavitation zones in a reactor volume, metal contamination in horn type of reactors, very low energy efficiency and high capital as well as operating costs [55].

Unlike ultrasonic cavitation, hydrodynamic cavitation by its nature is more amenable for scaling up and for industrial scale implementation. Hydrodynamic cavitation is realized by forcing liquid to flow through specifically designed fluidic devices which are configured in such a way that a single or multiple low pressure zones are realized. Cavities are generated in such low pressure regions and travel with the flowing liquid. Typically, flow in these devices is in the turbulent regime. The inception of cavitation may therefore happen even when time averaged local pressure is higher than vapor pressure. When cavities traveling with liquid are exposed to higher pressures and turbulent pressure fluctuations, these cavities collapse and can be harnessed for achieving desired physico-chemical transformations. Hydrodynamic cavitation has all the desired attributes required for successful implementation in industrial processes. In last two decades, there is tremendous interest in developing and applying hydrodynamic cavitation based processes. Several examples of such applications are cited at the beginning of this chapter. Though the idea of generating low pressure zones and thereby realizing cavities which may be harnessed for desired application looks simple, the lack of systematic basis for designing hydrodynamic cavitation devices and lack of understanding of how to simulate physico-chemical effects of generated cavities in such devices is a bottleneck. This book attempts to provide systematic framework for developing devices, design approaches and applications of hydrodynamic cavitation. The following section provides a general introduction to hydrodynamic cavitation devices.

1.2 Hydrodynamic Cavitation Devices

Hydrodynamic cavitation devices can be broadly classified into two types, namely, with and without moving parts (Figure 1.3). Devices with moving parts usually involve a rotor – an impeller rotating at high speed and a stator with a small clearance between rotor and stator. The surface of rotor or stator may have dents or dimples of appropriate size, shape and depth which facilitate generation of low pressure regions and consequently, cavitation. The inception and extent of cavitation depends on specific configuration of rotor – stator, rotating speed and net flow rate of liquid through the device. See for example Petkovšek et al. [56] and Garlicka et al. [57]. Rotor–stator based cavitation devices are expensive, energy intensive and require maintenance leading to higher operational costs. Despite the limitations, rotor-stator based devices have been proposed and used for wastewater treatment [58] and for biomass pre-treatment [59].

Hydrodynamic cavitation devices without any moving parts are designed to generate low pressure zones within the device by manipulating the flow field. Typically, realizing high velocity zones by virtue of geometric configuration of device generates desired low pressure. Broadly speaking, such passive hydrodynamic cavitation devices either use small constrictions and linear flow through these constrictions or use strongly swirling flows for generating low pressure regions. Typical examples of such devices and corresponding pressure profiles are shown schematically in Figure 1.4. The presence of small constrictions used in linear flow based device may

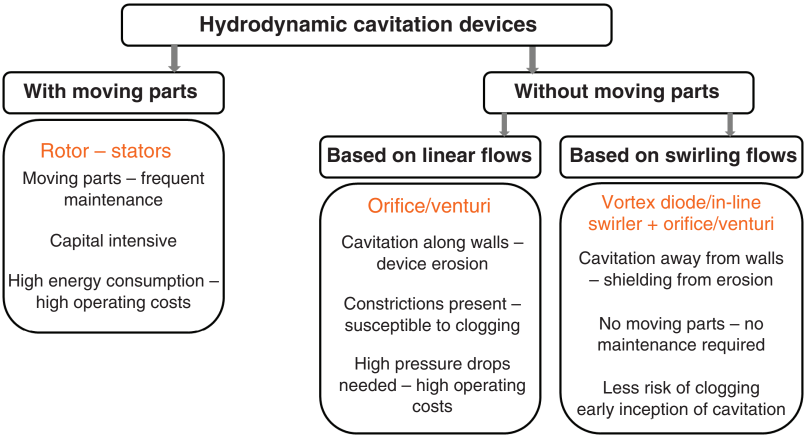

Figure 1.3 Classification of hydrodynamic cavitation devices.

pose a risk of clogging when handling liquids containing suspended solids (which is not uncommon for many wastewater or other biomass pre-treatment applications). In such devices, the cavitation bubble collapse occurs near the walls and therefore devices are susceptible to erosion [38]. Swirling flow based devices developed by Ranade et al. [61] overcome some of these disadvantages. In these vortex based devices, the flowing fluid enters the circular chamber tangentially, leading to a free vortex flow. When the free vortex is converted to a forced vortex at the axial port exit, cavitation is generated. The mode of generation of cavities in vortex based devices involve a swirl flow and therefore does not require very small constrictions and generate cavities in the core of the flowing liquid [38]. Such devices are much less susceptible to clogging than conventional orifice or venturi based devices. More importantly, the cavity collapse occur in the vortex core of the flowing fluid. This naturally shields the device walls from erosion. It is also possible to develop passive hydrodynamic cavitation devices by combining swirling and linear flows. For example, a commercially available cavitation device, Dynaswirl [62] or use of inline swirlers by Simpson and Ranade [38]. However, such devices still are based on small constrictions and therefore may inherit some of the disadvantages of conventional linear flow based devices.

Newer hydrodynamic cavitation devices are being developed and several attempts are being made to commercialize these devices. For example, Biobang/Cavimax (www.biobang.com) is commercializing rotor – stator based devices, HyCa Technologies (www.hycator.com) is commercializing linear flow based devices, VIVIRA Process Technologies (www.vivira.in) is commercializing vortex diode as well as hybrid devices based on in-line swirler designs. It is important to develop systematic basis for comparing such different devices.

Apart from the geometric configuration of the hydrodynamic cavitation devices, selecting an appropriate range for operation is also important. In all such hydrodynamic cavitation devices, the inception of cavitation occurs at a certain flow rate which is a function of device design, characteristic of liquid, presence of suspended solids or dissolved gases and operating temperature. As the flow rate increases,

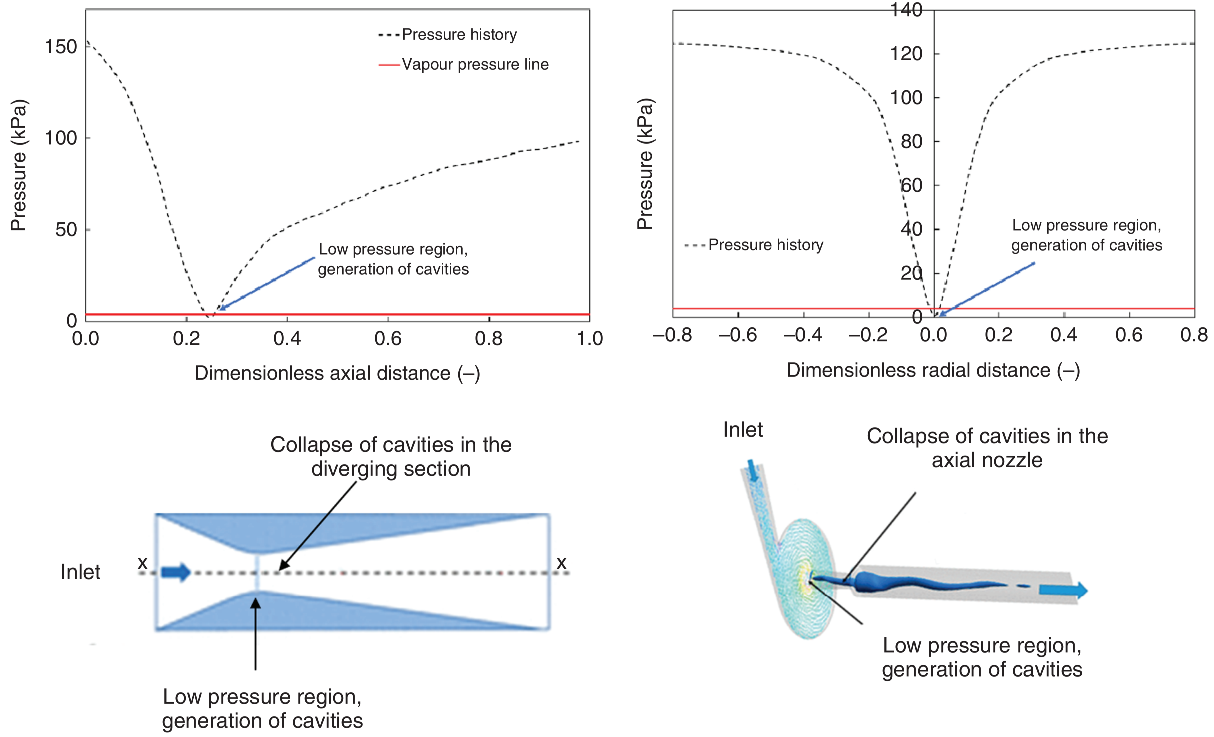

Figure 1.4 Pressure profile in linear flow based cavitation device and swirling flow based cavitation device (Source: Adapted from [38, 60]).

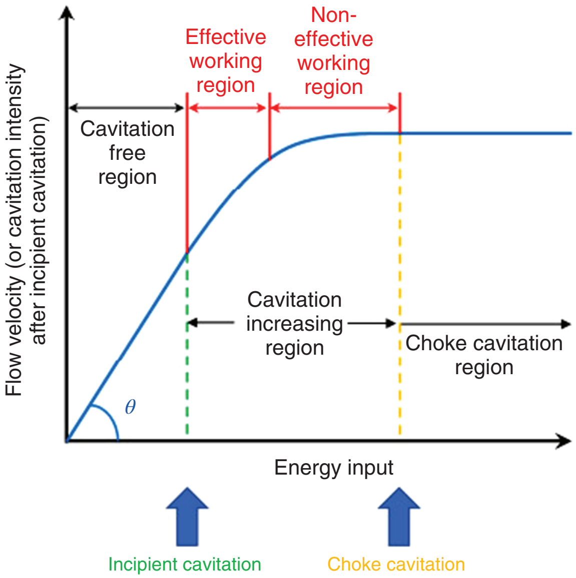

Figure 1.5 Different cavitation regimes as a function of flow rate or energy input (Source: From [37]/with permission of Elsevier).

extent of cavitation increases up to a certain limit. Beyond a certain threshold, choked cavitation is realized. This is schematically shown in Figure 1.5.

For appropriate selection of geometric configuration and operating conditions of hydrodynamic cavitation devices, it is essential to develop an ability to quantitatively simulate cavitating flows in such devices and thereby estimate overall process performance, facilitate optimisation and scale-up. Development of computational models for simulating performance of cavitation devices is not straight forward primarily because of existence of a wide range of spatio-temporal scales (single cavity with characteristic scales of $\sim10^{-6}$ m, $\sim10^{-4}$ s to cavitation device scale of $\sim10^{0}$ m, $\sim10^{0}$ s). Different types of models have been proposed and used in previous studies. Flow models range from a single cavity (for example, Gireesan and Pandit [63], Pawar et al. [64], and Pandit et al. [32]) to device scale computational fluid dynamics models (for example, Simpson and Ranade [65]). For estimating overall performance, typically reaction engineering models are used (Holkar et al. [6], Ranade and Bhandari [7], and references cited therein). Many such studies use and report pseudo-first order rate constants to describe performance of hydrodynamic cavitation process/device (for example, Rajoriya et al. [66], Capocelli et al. [67], and Saharan et al. [68]). Use of such a pseudo-rate constant which is a function of cavitation device configuration, operating conditions and number of passes through cavitation device is rather misleading and cannot be used to compare different cavitation devices. Some attempts have also been made to develop empirical correlation of performance with design and operating parameters (for example, see Sharma et al. [69]). However, such correlations have very limited applicability considering a wide variety of devices being used in practice. Detailed multi-scale or multi-layer computational fluid dynamics (CFD) models may potentially help to develop an ability to make quantitative simulations of flow and performance of hydrodynamic cavitation devices. The previously published studies on flow models may be broadly categorized into two groups: the first group focuses on detailed flow characteristics rather than performance of cavitation device/process (see for example, Ma et al. [70] and Hsiao et al. [71]). The second group focuses on simulating performance of cavitation devices using rather simplified CFD models (see for example, Capocelli et al. [72]). It is important to systematically present designs of hydrodynamic cavitation devices, experimental set-up required to evaluate performance of such devices and a suite of computational models useful for simulating hydrodynamic cavitation devices and processes based on those devices. In this book (Part 1), such an attempt is made. A brief introduction to applications of hydrodynamic cavitation is included in the following section.

1.3 Applications of Hydrodynamic Cavitation

As discussed earlier, hydrodynamic cavitation involves rapid phase change and generation of localized high pressure and temperature regions. Intense shear and high velocity jets as well as strongly oxidizing radicals are generated. These physico-chemical effects of cavitation can be harnessed for a variety of applications. Large number of studies reporting applications of hydrodynamic cavitation may be broadly classified into three groups as shown in Figure 1.6.

Several reviews listing these applications have been published. For example, see recent reviews by Tao et al. [73], Carpenter et al. [5], Albanese et al. [74], Holkar et al. [6], Panda et al. [75], Sun et al. [76] and Mancuso et al. [77]. Most of these reviews however primarily list various applications and provide only cursory information and therefore not very useful. Three major applications of hydrodynamic cavitation are wastewater treatment, water disinfection and pre-treatment of biomass. In this book, we have included dedicated chapters for these three applications. These primarily harness generation of oxidizing radicals as well as intense shear via cavity collapse. We have also summarized other applications. However, an attempt has been made to connect those applications of hydrodynamic cavitation to device design and wherever possible to modeling. The goal is not just to list the applications but provide adequate information to the reader so as to facilitate further work or implementation in practice. Each application, of course, will require corresponding domain knowledge and it is not possible to include all the intricacies with respect to numerous applications. However, an attempt is made here to present generic approach while discussing selected applications so that the approach may be adapted for applications not included in this book. The overall organisation of the book is briefly discussed in the following section.

1.4 Organization of the Book

The information in this book is organized to facilitate systematic understanding of hydrodynamic cavitation. The focus is on providing adequate framework for design of hydrodynamic cavitation devices, modeling of processes based on such

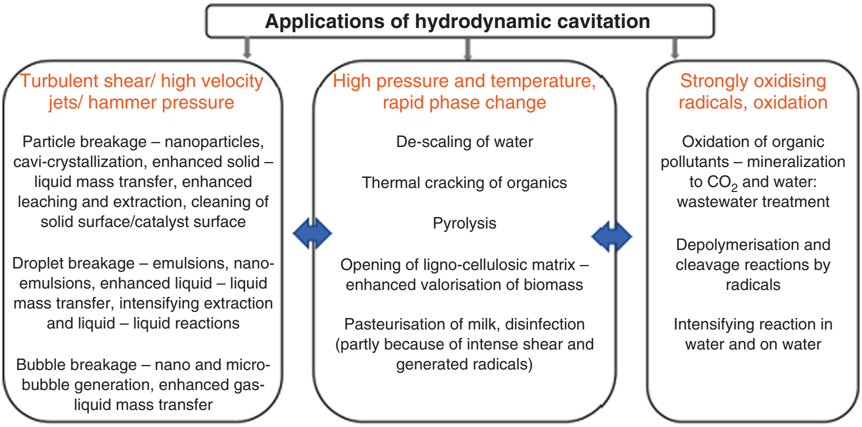

Figure 1.6 Applications of hydrodynamic cavitation.

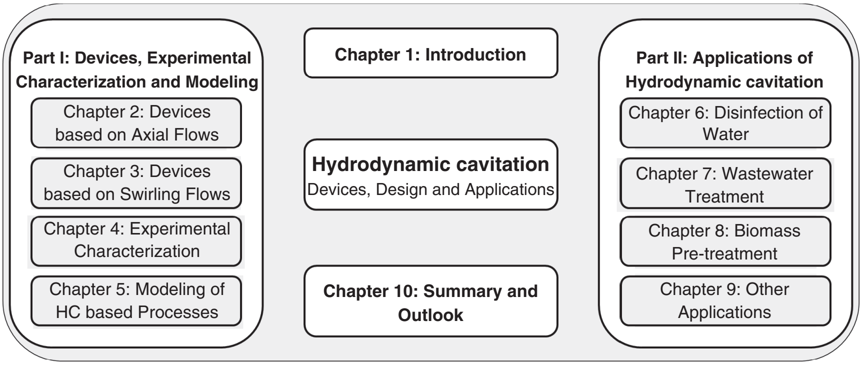

Figure 1.7 Organization of the book.

devices (experimentally as well as computationally) and developing applications of hydrodynamic cavitation. We have restricted the scope of this book to primarily discuss hydrodynamic cavitation realized by passive devices (without any moving parts). The material in this book is organized mainly in two parts (see the overall structure shown in Figure 1.7).

The first part presents design aspects of hydrodynamic cavitation and the second part presents various applications. These two parts precede with this introductory chapter. The last chapter on summary and outlook is included after the second part.

The first part comprises four chapters. Chapter 2 covers flow characteristics of hydrodynamic cavitation devices based on linear or axial flows. This primarily includes two most widely used cavitation devices namely orifice and venturi. Over the years, significant experimental data and information on these two devices have been accumulated. This chapter presents detailed computational fluid dynamics based models to provide useful insights and discuss various key design parameters of such cavitation devices. Some of the disadvantages of these linear flow based devices are highlighted. Hydrodynamic cavitation devices based on swirling flows are discussed in Chapter 3. The advantages realized by using swirling flows are highlighted. CFD models are used for bringing out key characteristics and key design parameters. Together these two chapters will provide adequate information on development and application of CFD models for simulating flow characteristics of hydrodynamic cavitation devices and clearly bring out the key design parameters. The presented discussion will not only be useful for further improvement and optimisation of devices discussed in this book, but will also be useful for developing new and better hydrodynamic cavitation devices.

Chapters 4 and 5 provide ways of experimentally characterizing various hydrodynamic cavitation devices and computationally modeling performance of processes based on cavitation devices, respectively. Key components of typical experimental set-up required to characterize and quantify performance of hydrodynamic cavitation devices are discussed in Chapter 4. Some of the common pitfalls in designing the experimental set-up are highlighted and recommendations to avoid these are included. The experimental investigations are mainly carried out to identify first inception of cavitation and then quantification of performance. Brief discussion on planning and executing such experiments on inception and quantification of performance is included. Specific recommendations are discussed. Chapter 4 and references cited therein will provide useful information for designing experimental set-up and carrying out experiments to characterize hydrodynamic cavitation devices.

Computational models for interpreting experimental data on performance of hydrodynamic cavitation devices and processes are discussed in Chapter 5. The processes based on hydrodynamic cavitation essentially use generated shear, localized hot spots, and hydroxyl radicals for realizing various physico-chemical transformations. Various approaches ranging from empirical models to rigorous multi-layer computational models for modeling hydrodynamic cavitation based transformation processes are discussed. Large number of studies use the empirical approaches – either based on effective rate constant or per-pass performance factor where these empirical parameters are obtained using the experimental data. These models are discussed in detail and compared with each other. A brief discussion on recently published studies about the possibility of developing Artificial Neural Networks (ANN’s) based models is also included. After discussing these empirical models, physics based models starting with a single cavity to multiphase applications based on hydrodynamic cavitation are presented. A need for simultaneous application of multiple modeling approaches is highlighted. Some comments on future outlook and further advances in modeling of hydrodynamic cavitation based processes are also included.

The second part of the book presents various applications of hydrodynamic cavitation. Three major applications namely disinfection of water, wastewater treatment and pre-treatment of biomass are discussed in Chapters 6, 7, and 8, respectively. Chapter 6 is dedicated to discuss investigations of hydrodynamic cavitation based disinfection of water. Safe drinking water is important to mankind and quality of life, thus the disinfection of water by efficient processes becomes pertinent. This chapter discusses the advantages that cavitation could offer over conventional techniques.

Here the possibility of the technology as a standalone process to break down harmful microorganisms is discussed. Studies which have investigated the possibilities to enhance the performance of the cavitation process with hydrogen peroxide, ozone and aeration are discussed. Recent investigations to enhance the cavitation based disinfection with natural oils are discussed. The discussion will be useful for harnessing hydrodynamic cavitation for the disinfection of water with no or minimal use of other chemicals.

Chapter 7 discusses the wastewater treatment application. Water serves many functions in manufacturing industries and eventually ends up as wastewater. The contaminated and pollutant containing wastewater may have significantly higher chemical oxygen demand (COD) than permissible limits. It is therefore essential to treat such wastewater for oxidizing pollutants/species causing higher COD. Application of hydrodynamic cavitation which generates strongly oxidizing radicals for treating wastewater is discussed in Chapter 7. Published studies are critically reviewed to identify key process parameters and their influence on overall performance. These process parameters include operating temperature, pH, pressure drop across cavitation devices and initial COD levels. Possible ways of augmenting performance of hydrodynamic cavitation including use of aeration, addition of hydrogen peroxide or ozone and photocatalysis have also been briefly discussed. The discussion will be useful for developing intensified wastewater treatment processes based on hydrodynamic cavitation.

Application of hydrodynamic cavitation for enhancing valorisation of lignocellulosic biomass is discussed in Chapter 8. The key step in any such valorisation process of biomass is pre-treatment, which opens up complex lignocellulosic matrix and makes the cellulose and hemicellulose accessible for further chemical or biochemical process steps. Hydrodynamic cavitation can be used as a stand alone pre-treatment method or as a tool for intensifying other chemical based pre-treatments. Use of hydrodynamic cavitation for two key application areas namely bioethanol and biogas production is discussed. Key aspects are reviewed and influence of important process parameters on overall performance are brought out. The discussion will be useful for exploiting hydrodynamic cavitation for valorisation of a variety of complex biomass resources. Some comments on how hydrodynamic cavitation based bio-refineries may be developed are also included.

It is impossible to include every application of hydrodynamic cavitation in any book. Attempt is made here to present a generic approach towards development and optimisation of applications using hydrodynamic cavitation. Beyond these three major applications, additional applications are grouped by fundamental types such as gas–liquid, liquid–liquid and solid–liquid in Chapter 9. These applications namely floatation, oxidative desulphurization, emulsification, biodiesel production, cavi-crystallization and nano-particle generation are briefly reviewed. The key issues in the conventional processing are identified, the role of hydrodynamic cavitation is suggested, and the key studies in these application areas are provided as a directive to the reader.

In the last chapter of the book (Chapter 10), the current state of art on design of hydrodynamic cavitation devices and processes is summarized. A need for developing better multi-scale models and multi-layer models is emphasized. Need to develop appropriate verification, validation and model calibration practices is discussed. The lessons learnt from our experience of applying computational flow modeling to hydrodynamic cavitation based processes are briefly summarized. Some comments on selecting right level of complexity and modeling approach are included. Availability of non-invasive sensors such as acoustic sensors, real-time data processing, advances in multiphase flow modeling and machine learning may open up opportunities for developing high-fidelity computational models of hydrodynamic cavitation based processes. Besides comments on design and modeling, some discussion on current trends and outlook on hydrodynamic cavitation based applications are included. We hope that this book provides a framework and useful guidelines for harnessing hydrodynamic cavitation for a wide range of applications.

References

1 Brennen, C.E. (2014). *Cavitation and Bubble Dynamics*. Cambridge University Press.

2 Shah, Y.T., Pandit, A.B., and Moholkar, V.S. (1999). *Cavitation Reaction Engineering*. Springer Science & Business Media.

3 Suslick, K.S., Mdleleni, M.M., and Ries, J.T. (1997). Chemistry induced by hydrodynamic cavitation. *Journal of the American Chemical Society* 119 (39): 9303–9304.

4 Li, S. (2015). Tiny bubbles challenge giant turbines: three gorges puzzle. *Interface Focus* 5 (5): 20150020.

5 Carpenter, J., Badve, M., Rajoriya, S. et al. (2017). Hydrodynamic cavitation: an emerging technology for the intensification of various chemical and physical processes in a chemical process industry. *Reviews in Chemical Engineering* 33 (5): 433–468.

6 Holkar, C.R., Jadhav, A.J., Pinjari, D.V., and Pandit, A.B. (2019). Cavitationally driven transformations: a technique of process intensification. *Industrial and Engineering Chemistry Research* 58 (15): 5797–5819.

7 Ranade, V.V. and Bhandari, V.M. (2014). *Industrial Wastewater Treatment, Recycling and Reuse*. Butterworth-Heinemann.

8 Gągol, M., Przyjazny, A., and Boczkaj, G. (2018). Wastewater treatment by means of advanced oxidation processes based on cavitation – a review. *Chemical Engineering Journal* 338: 599–627.

9 Sarvothaman, V.P., Nagarajan, S., and Ranade, V.V. (2018). Treatment of solvent-contaminated water using vortex-based cavitation: influence of operating pressure drop, temperature, aeration, and reactor scale. *Industrial and Engineering Chemistry Research* 57 (28): 9292–9304.

10 Sarvothaman, V.P., Simpson, A.T., and Ranade, V.V. (2019). Modelling of vortex based hydrodynamic cavitation reactors. *Chemical Engineering Journal* 377: 119639.

11 Suryawanshi, P.G., Bhandari, V.M., Sorokhaibam, L.G. et al. (2018). Solvent degradation studies using hydrodynamic cavitation. *Environmental Progress & Sustainable Energy* 37 (1): 295–304.

12 Patil, P.B., Bhandari, V.M., and Ranadec, V.V. (2021). Wastewater treatment and process intensification for degradation of solvents using hydrodynamic cavitation. *Chemical Engineering and Processing Process Intensification* 108485.

13 Gaikwad, V. and Ranade, V. (2016). Disinfection of water using vortex diode as hydrodynamic cavitation reactor. *Asian Journal of Chemistry* 28 (8): 1867.

14 Jain, P., Bhandari, V.M., Balapure, K. et al. (2019). Hydrodynamic cavitation using vortex diode: an efficient approach for elimination of pathogenic bacteria from water. *Journal of Environmental Management* 242: 210–219.

15 Mane, M.B., Bhandari, V.M., Balapure, K., and Ranade, V.V. (2020). A novel hybrid cavitation process for enhancing and altering rate of disinfection by use of natural oils derived from plants. *Ultrasonics Sonochemistry* 61: 104820.

16 Mane, M.B., Bhandari, V.M., and Ranade, V.V. (2021). Safe water and technology initiative for water disinfection: application of natural plant derived materials. *Journal of Water Process Engineering* 43: 102280.

17 Mane, M.B., Bhandari, V.M., Balapure, K., and Ranade, V.V. (2020). Destroying antimicrobial resistant bacteria (AMR) and difficult, opportunistic pathogen using cavitation and natural oils/plant extract. *Ultrasonics Sonochemistry* 69: 105272.

18 Suryawanshi, N.B., Bhandari, V.M., Sorokhaibam, L.G., and Ranade, V.V. (2016). A non-catalytic deep desulphurization process using hydrodynamic cavitation. *Scientific Reports* 6 (1): 1–8.

19 Suryawanshi, N.B., Bhandari, V.M., Sorokhaibam, L.G., and Ranade, V.V. (2017). Developing techno-economically sustainable methodologies for deep desulfurization using hydrodynamic cavitation. *Fuel* 210: 482–490.

20 Uebe, J., Kryževičius, Ž., Janutėnienė, J. et al. (2021). Desulfurizing of pyrolysis oil of used tires using a 3D-printed vortex diode and modeling of process. *Journal of Marine Science and Engineering* 9 (8): 876.

21 Nakashima, K., Ebi, Y., Shibasaki-Kitakawa, N. et al. (2016). Hydrodynamic cavitation reactor for efficient pretreatment of lignocellulosic biomass. *Industrial and Engineering Chemistry Research* 55 (7): 1866–1871.

22 Terán Hilares, R., Ramos, L., da Silva, S.S. et al. (2018). Hydrodynamic cavitation as a strategy to enhance the efficiency of lignocellulosic biomass pretreatment. *Critical Reviews in Biotechnology* 38 (4): 483–493.

23 Nagarajan, S. and Ranade, V.V. (2019). Pretreatment of lignocellulosic biomass using vortex-based devices for cavitation: influence on biomethane potential. *Industrial and Engineering Chemistry Research* 58 (35): 15975–15988.

24 Maddikeri, G.L., Gogate, P.R., and Pandit, A.B. (2014). Intensified synthesis of biodiesel using hydrodynamic cavitation reactors based on the interesterification of waste cooking oil. *Fuel* 137: 285–292.

25 Malani, R.S., Shinde, V., Ayachit, S. et al. (2019). Ultrasound–assisted biodiesel production using heterogeneous base catalyst and mixed non–edible oils. *Ultrasonics Sonochemistry* 52: 232–243.

26 Albanese, L., Ciriminna, R., Meneguzzo, F., and Pagliaro, M. (2017). Beer-brewing powered by controlled hydrodynamic cavitation: theory and real-scale experiments. *Journal of Cleaner Production* 142: 1457–1470.

27 Pathania, S., Ho, Q.T., Hogan, S.A. et al. (2018). Applications of hydrodynamic cavitation for instant rehydration of high protein milk powders. *Journal of Food Engineering* 225: 18–25.

28 Díez, D., Urueña, A., Barrios, C., and Antolín, G. (2019). Valorization of rendering fats to produce biodiesel by single and multi orifice plate cavitation reactor. *Waste and Biomass Valorization* 10 (12): 3773–3780.

29 Didenko, Y.T., McNamara, W.B., and Suslick, K.S. (1999). Hot spot conditions during cavitation in water. *Journal of the American Chemical Society* 121 (24): 5817–5818.

30 Gogate, P.R. and Pandit, A.B. (2005). A review and assessment of hydrodynamic cavitation as a technology for the future. *Ultrasonics Sonochemistry* 12 (1–2): 21–27.

31 Rayleigh, L.V.I.I.I. (1917). On the pressure developed in a liquid during the collapse of a spherical cavity. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 34 (200): 94–98.

32 Pandit, A.V., Sarvothaman, V.P., and Ranade, V.V. (2021). Estimation of chemical and physical effects of cavitation by analysis of cavitating single bubble dynamics. *Ultrasonics Sonochemistry* 77: 105677.

33 Franc, J.-P. and Michel, J.-M. (2006). *Fundamentals of Cavitation*. Springer Science & Business Media.

34 Ozonek, J. (2012). *Application of Hydrodynamic Cavitation in Environmental Engineering*. CRC Press.

35 Gogate, P.R. and Pandit, A.B. (2004). A review of imperative technologies for wastewater treatment I: oxidation technologies at ambient conditions. *Advances in Environmental Research* 8 (3–4): 501–551.

36 Meijn, G.-J. (2015). *Physical Modeling of Cavitation Using an Enthalpy Based Model*. Delft, The Netherlands: Faculty of Mechanical, Maritime and Material Engineering; Delft University of Technology.

37 Sun, X., Liu, J., Ji, L. et al. (2020). A review on hydrodynamic cavitation disinfection: the current state of knowledge. *Science of the Total Environment* 737: 139606.

38 Simpson, A. and Ranade, V.V. (2019). 110th Anniversary: comparison of cavitation devices based on linear and swirling flows: hydrodynamic characteristics. *Industrial and Engineering Chemistry Research* 58 (31): 14488–14509.

39 Barnaby, S.W. (1902). Torpedo-boat destroyers. *Journal of the American Society for Naval Engineers* 14 (2): 396–408.

40 Barnaby, S.W. (ed.) (1906). *Note on the Cavitation of Screw Propulsion (Including Appendix)*. Thomas Telford-ICE Virtual Library.

41 Young, F.R. (1999). *Cavitation*. World Scientific.

42 Asaithambi, N., Singha, P., Dwivedi, M., and Singh, S.K. (2019). Hydrodynamic cavitation and its application in food and beverage industry: a review. *Journal of Food Process Engineering* 42 (5): e13144.

43 Gogate, P.R. and Kabadi, A.M. (2009). A review of applications of cavitation in biochemical engineering/biotechnology. *Biochemical Engineering Journal* 44 (1): 60–72.

44 Richards, W.T. and Loomis, A.L. (1927). The chemical effects of high frequency sound waves I. a preliminary survey. *Journal of the American Chemical Society* 49 (12): 3086–3100.

45 Vyas, S. and Ting, Y.-P. (2018). A review of the application of ultrasound in bioleaching and insights from sonication in (bio) chemical processes. *Resources* 7 (1): 3.

46 Sancheti, S.V. and Gogate, P.R. (2017). A review of engineering aspects of intensification of chemical synthesis using ultrasound. *Ultrasonics Sonochemistry* 36: 527–543.

47 Manickam, S., Sivakumar, K., and Pang, C.H. (2020). Investigations on the generation of oil-in-water (O/W) nanoemulsions through the combination of ultrasound and microchannel. *Ultrasonics Sonochemistry* 69: 105258.

48 Ojha, K.S., Mason, T.J., O'Donnell, C.P. et al. (2017). Ultrasound technology for food fermentation applications. *Ultrasonics Sonochemistry* 34: 410–417.

49 Wang, M. and Yuan, W. (2016). Modeling bubble dynamics and radical kinetics in ultrasound induced microalgal cell disruption. *Ultrasonics Sonochemistry* 28: 7–14.

50 Bystryak, S., Santockyte, R., and Peshkovsky, A.S. (2015). Cell disruption of S. cerevisiae by scalable high-intensity ultrasound. *Biochemical Engineering Journal* 99: 99–106.

51 Angelopoulos, C. (2018). Ultrasound in dentistry: toward a future of radiation-free imaging. *Dental Clinics of North America* 62 (3): 481–489.

52 Reissland, N., Francis, B., Kumarendran, K., and Mason, J. (2015). Ultrasound observations of subtle movements: a pilot study comparing foetuses of smoking and nonsmoking mothers. *Acta Paediatrica* 104 (6): 596–603.

53 Fernández-Lao, C., Cantarero-Villanueva, I., Galiano-Castillo, N. et al. (2016). The effectiveness of a mobile application for the development of palpation and ultrasound imaging skills to supplement the traditional learning of physiotherapy students. *BMC Medical Education* 16 (1): 1–7.

54 Ashokkumar, M. (2016). *Advantages, Disadvantages and Challenges of Ultrasonic Technology. Ultrasonic Synthesis of Functional Materials*, 41–42. Springer.

55 Sutariya, S., Sunkesula, V., Kumar, R., and Shah, K. (2018). Emerging applications of ultrasonication and cavitation in dairy industry: a review. *Cogent Food & Agriculture* 4 (1): 1549187.

56 Petkovšek, M., Mlakar, M., Levstek, M. et al. (2015). A novel rotation generator of hydrodynamic cavitation for waste-activated sludge disintegration. *Ultrasonics Sonochemistry* 26: 408–414.

57 Garlicka, A., Zubrowska-Sudol, M., Umiejewska, K. et al. (2020). Effects of thickened excess sludge pre-treatment using hydrodynamic cavitation for anaerobic digestion. *Energies* 13 (10): 2483.

58 Zhao, Z., Wang, L., Fan, J. et al. (2020). Degradation of indigo carmine by coupling Fe (II)-activated sodium persulfate and ozone in a rotor-stator reactor. *Chemical Engineering and Processing Process Intensification* 148: 107791.

59 Garuti, M., Langone, M., Fabbri, C., and Piccinini, S. (2018). Monitoring of full-scale hydrodynamic cavitation pretreatment in agricultural biogas plant. *Bioresource Technology* 247: 599–609.

60 Sarvothaman, V.P. (2020). *Hydrodynamic Cavitation for Effluent Treatment: Using Vortex-Based Cavitation Devices*. Queen's University Belfast.

61 Ranade, V.V., Kulkarni, A.A., and Bhandari, V.M. (2016). inventors Vortex diodes as effluent treatment devices. Patent US9422952B2.

62 Dynaflow. Dynajets cavitating jets 2021. http://www.dynaflow-inc.com/Products/Jets/Jets-Cavitating.htm.

63 Gireesan, S. and Pandit, A.B. (2017). Modeling the effect of carbon-dioxide gas on cavitation. *Ultrasonics Sonochemistry* 34: 721–728.

64 Pawar, S.K., Mahulkar, A.V., Pandit, A.B. et al. (2017). Sonochemical effect induced by hydrodynamic cavitation: comparison of venturi/orifice flow geometries. *AIChE Journal* 63 (10): 4705–4716.

65 Simpson, A. and Ranade, V.V. (2019). Flow characteristics of vortex based cavitation devices: computational investigation on influence of operating parameters and scale. *AIChE Journal* 65 (9): e16675.

66 Rajoriya, S., Bargole, S., George, S., and Saharan, V.K. (2018). Treatment of textile dyeing industry effluent using hydrodynamic cavitation in combination with advanced oxidation reagents. *Journal of Hazardous Materials* 344: 1109–1115.

67 Capocelli, M., Prisciandaro, M., Lancia, A., and Musmarra, D. (2014). Hydrodynamic cavitation of p-nitrophenol: a theoretical and experimental insight. *Chemical Engineering Journal* 254: 1–8.

68 Saharan, V.K., Badve, M.P., and Pandit, A.B. (2011). Degradation of Reactive Red 120 dye using hydrodynamic cavitation. *Chemical Engineering Journal* 178: 100–107.

69 Sharma, A., Gogate, P.R., Mahulkar, A., and Pandit, A.B. (2008). Modeling of hydrodynamic cavitation reactors based on orifice plates considering hydrodynamics and chemical reactions occurring in bubble. *Chemical Engineering Journal* 143 (1–3): 201–209.

70 Ma, J., Hsiao, C.-T., and Chahine, G.L. (2017). A physics based multiscale modeling of cavitating flows. *Computers and Fluids* 145: 68–84.

71 Hsiao, C.-T., Ma, J., and Chahine, G.L. (2017). Multiscale tow-phase flow modeling of sheet and cloud cavitation. *International Journal of Multiphase Flow* 90: 102–117.

72 Capocelli, M., Musmarra, D., Prisciandaro, M., and Lancia, A. (2014). Chemical effect of hydrodynamic cavitation: simulation and experimental comparison. *AIChE Journal* 60 (7): 2566–2572.

73 Tao, Y., Cai, J., Huai, X. et al. (2016). Application of hydrodynamic cavitation to wastewater treatment. *Chemical Engineering and Technology* 39 (8): 1363–1376.

74 Albanese, L. and Meneguzzo, F. (2019). *Hydrodynamic Cavitation-Assisted Processing of Vegetable Beverages: Review and the Case of Beer-Brewing*, 211–257. Production and Management of Beverages.

75 Panda, D., Saharan, V.K., and Manickam, S. (2020). Controlled hydrodynamic cavitation: a review of recent advances and perspectives for greener processing. *Processes* 8 (2): 220.

76 Sun, X., Chen, S., Liu, J. et al. (2020). Hydrodynamic cavitation: a promising technology for industrial-scale synthesis of nanomaterials. *Frontiers in Chemistry* 8: 259.

77 Mancuso, G., Langone, M., and Andreottola, G. (2020). A critical review of the current technologies in wastewater treatment plants by using hydrodynamic cavitation process: principles and applications. *Journal of Environmental Health Science and Engineering* 18 (1): 311–333.